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RTR 250–01

(NASA-CR-193879) ANALYSIS AND EFFECTS OF THE ADVANCED SOLID ROCKET MOTOR ON THE SPACE SHUTTLE ELEMENTS Interim Final Report (Remtech) 44 p

N94-24664

Unclas

G3/16 0204179

ANALYSIS AND EFFECTS OF THE ADVANCED SOLID ROCKET MOTOR ON THE SPACE SHUTTLE ELEMENTS

INTERIM FINAL REPORT

October 15, 1993

Submitted to:

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

Contract:

NAS8–39235

By:

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PREFACE

REMTECH, Inc., and its subcontractors, SECA, Inc., of Huntsville, Alabama, and Physical Sciences, Inc., of Andover, Massachusetts, have analyzed and generated induced thermal environments for the ASRB and other elements of the ASRB/Shuttle integrated vehicle under Contract NAS8–39235. The induced thermal environments begin with the launch stand plume impingement environment at liftoff, continue with plume induced base heating and aerodynamic heating during ascent, include the environments to the ASRBs due to SSME plume impingement following separation, and conclude with aerodynamic heating to the ASRBs during reentry leading to splashdown.

Contract NAS8–39235 supports Level II and Level III ASRB program requirements and schedules for the five-year period from October 1, 1991, through September 30, 1996. This interim final report summarizes the major activities and accomplishments for the initial two years of the contract ending September 30, 1993. Technical guidance and overall direction for this effort has been provided by Mr. Peter Sulyma of the Induced Environment Branch ED-33, NASA/Marshall Space Flight Center in Huntsville, Alabama.

Contents

Section 1
SUMMARY

This interim final report summarizes the activities and major accomplishments under NASA/MSFC Contract NAS8–39235 for the initial two year contractual effort beginning October 1, 1991, and ending September 30, 1993. It is not intended as an exhaustive treatment or review of any particular technical issue which was addressed during this two-year period, but does provide an overview of the many induced environment studies and test support activities undertaken by REMTECH and its subcontractors during this two-year period.

The initial scope of work has been pursued vigorously through this two-year period by separating the effort into five functional areas. The five functional areas are ascent plume radiation, ascent plume convection, ascent aerodynamic heating, launch stand environments, and reentry heating. A work breakdown structure (WBS) for each functional area was devised to permit nearly autonomous activities within each functional responsibility while maintaining commonality in reporting procedures and cost accounting. The contract was modified 11 times to provide incremental funding and to expand the scope of work. Additional work breakdown structure was incorporated to meet the expanded scope.

A contract chronology is provided in Section 2. The initial scope of work, expanded scope, and corresponding WBS designation are described in Section 3. A summary review of major accomplishments is also provided in Section 4 to show the breadth of activities and extent of reporting. Reports, meetings, test activities, and other accomplishments within each functional area are also summarized by WBS heading in the appendices.

Section 2
CONTRACT CHRONOLOGY

The contract was awarded, effective October 1, 1991, for two years with three one-year options. During the two-year period from October 1, 1991, through September 30, 1993, the contract was modified 11 times. Dates and purposes of the modifications are summarized below:

Modification 1	10/9/91	Administrative Change
Modification 2	1/3/92	Administrative Change
Modification 3	1/13/92	Incremental Funds Added
Modification 4	3/9/92	Revised SOW WBS 1000 (PSI Subcontract)
Modification 5	4/28/92	Revised SOW WBS 2000 (NLS Study)
Modification 6	7/30/92	Add Funding for Modifications 4 and 5
Modification 7	11/13/92	Incremental Funds Added
Modification 8	2/12/93	Incremental Funds Added
Modification 9	3/23/93	Extended Period of Performance
Modification 10	6/30/93	Incremental Funds Added
Modification 11	9/29/93	Exercised Option Year 1 - Incremental Funds Added

Modifications 4 and 5 expanded the scope of work to include a set of experiments to provide initial data on gas effects on Al_2O_3 particle properties, and an assessment of the effect of utilizing ASRMs for the National Launch System (NLS), respectively. These two studies were completed and final reports issued in August 1992 for the NLS study and September 1993 for the molten Al_2O_3 investigation.

Section 3
SCOPE

The objective of Contract NAS8–39235 is to define the induced thermal environments for the ASRB and other elements of the ASRB/Shuttle integrated vehicle. The induced thermal environments begin with the launch stand plume impingement environment at liftoff, continue with plume induced base heating and aerodynamic heating during ascent, include the environments to the ASRB due to SSME plume impingement following separation, and conclude with aerodynamic heating to the ASRBs during reentry leading to splashdown.

The work breakdown structure to accomplish definition of these environments and responsible organizations are shown below:

WBS	TASK	RESPONSIBLE ORGANIZATION
1000	Ascent Plume Radiation	REMTECH (SECA)
2000	Ascent Plume Convection	REMTECH (SECA)
3000	Ascent Aerodynamic Heating	REMTECH
4000	Launch Stand Environments	SECA
5000	Reentry Heating	REMTECH
5100	SSME Plume Impingement	REMTECH (SECA)
6000	NLS Impact Study	REMTECH
7000	Molten Al_2O_3 Radiation Characteristics	PSI

As noted above, the primary role for SECA, Inc., was to define launch stand environments; however, SECA also provided important plume definitions in support of WBS 1000, 2000, and 5100. A continuous effort throughout the past two years has also been devoted to specification and coordination of development flight instrumentation which impacts WBS 1000, 2000, 3000, 5000, and 5100. Test support to subscale motor firings at MSFC and full scale motor tests in Utah was provided under WBS 1000.

Section 4
SUMMARY OF ACTIVITIES AND ACCOMPLISHMENTS

ASRM Level II and Level III program support by REMTECH and its subcontractors met or exceeded contract requirements during the first two years of effort. The program schedule has continued to slide, however, which resulted in some activities being extended compared with the proposal plan. A summary of major milestones met during FY 1992 (the first year of the contract) is presented below:

- Major Milestones Met During FY 1992
  - Cycle 1.5 Base heating Environment Published and Approved
  - Cycle 2 Launch Stand Environment Published and Approved
  - Cycle 1.5 BSRM Plume Impingement Environment Published and Approved
  - Cycle 1 Reentry Data Book Published and Approved
  - DFI Requirements Accepted by Level II and III
  - NLS 2 Base Heating Environment Published and Approved
  - Design and Fabrication of Venting Test Hardware Completed
  - MNASA Test Support and Radiometer Calibration Provided
  - PSI Subcontract Initiated

During the second year, many of the activities initiated during the first year were continued and intensified. Methodology development for Cycle 2 environments was a major activity, culminating in a full review for the ASRM Thermal Panel in June 1993. Major milestones during the second year are summarized below:

- Major Milestones Met During FY 1993
  - Cycle 2 Base Heating Methodology Approved
  - HGF Venting Test Completed and Documented
  - DFI Guidelines Assembled and Documented
  - PESST Test/MNASA Test Support/Data Review Continued
  - Argon Shock Tube Firings/Ionic Plume Characterization Study Completed and Documented
  - BSRM Plume Characterization Completed.
  - SSME Plume Impingement Analysis Initiated
  - Pre-Cycle 2 ASRB Base Heating Environment Defined and Delivered

In addition to the test support and instrumentation coordination activities which occurred throughout the two-year period, other general program support was provided as needed, including presentations, participation in telecons, and travel. A summary of the program support is presented below:

- FY 92 and FY 93 Program Support
  - Reports and Other Documentation

    7 Major Technical Reports
    ≈55 Technical Notes
  - Telecons

    ≈52 with Thermal Panel, NLS Induced Environment Panel, DFI Working Group, etc.
  - Presentations

    ≈36 with Thermal Panel, NLS, DFI, MNASA Test Working Groups
  - Travel

    ≈7 Trips: AFSIG at JSC, ASRM PDR at Iuka, ET Geometry Review at MMC Michoud, Methodology Review for JANNAF and AIAA, Instrumentation at MMC Michoud and Iuka.

Details of these activities and documentation are provided in the appendices by WBS category.

Section 5
PLANS FOR OPTION YEAR 1

The latest program schedule is based upon first launch of the Shuttle with ASRB in December 2000. To support this schedule, the Cycle 2 base heating environments definition and documentation are planned for completion in September 1994. Generation of these environments is the primary goal for Option Year 1 (FY 1994). A list of planned objectives is provided below:

- Generation and Documentation of Cycle 2 Environments
- Continued Participation in DFI Planning and Coordination
- Planning for Full-Scale Development Motor Firings
- Continued Review of Ascent Aeroheating Environments
- Definition of SSME Plume Impingement Environments to ASRBs Following Separation

Appendix A
WBS 1000 — Ascent Plume Radiation

There were four major areas of work under the Ascent Plume Radiation Task: Experimental Programs, Radiation Methodology, Plume Property Prediction Methodology, and Environment Prediction.

Experimental Program work was organized to support radiation measurement requirements providing data to verify prediction models on the series of MNASA motor tests at MSFC, TEM tests at Thiokol (Utah), ASRM static tests at Stennis Space Center, and ASRM flight tests. Work on specific tests during the contract period included MNASA-6 through 13 and TEM-8 and 11.

Radiation Methodology work was directed toward developing the necessary plume radiation models and geometry input files to predict plume radiation. This work included development of necessary computer codes and many predictions in support of plume property prediction band model development. Tasks necessary in the verification and development of radiation models required extensive work in developing a DFI database and the necessary codes to manipulate and adjust the data and separate the SSME and SRB plume radiation contributions. The required results are documented SSME and ASRB radiation models adapted to many zones defined on the Shuttle to provide: a sea-level plume radiation model, altitude adjustment functions to reflect trajectory parameters, gimbal sensitivity adjustments to provide margins for possible nozzle deflections, and computer input files providing geometric descriptions of design body point locations and shading surfaces.

Plume Property Prediction Methodology work was aimed at developing plume property prediction methods consistent with minor modifications of existing codes which, in combination with radiation prediction methods, could duplicate measurements of radiation from both ground and flight tests.

Environment Prediction tasks use the plume property and radiation models to predict radiation as a function of time and altitude for the required design body points and the design trajectories. The major environment prediction in the contract period was the Cycle 1.5 ASRB ascent plume heating for the External Tank (ET). However, many other limited environments were predicted to provide additional body points on the ASRB and comparisons of the new radiation models with current environments for the SRB and ET.

WBS 1000 FIRST YEAR ACTIVITIES (10/1/91-9/30/92)

OBJECTIVE	PUBLICATION	DATE
Experimental Programs		
• MNASA-6 through 10 radiometer arrangements, theoretical comparisons and radiometer calibration.		
• Evaluation of results from TEM-8 measurements.		
• Requirements for the ASRM static firing plume radiation measurements.	RTN 250-1-03 RTN 250-1-08	12/91 3/92
• Preparation of DFI radiometer requirements for the ASRM flight tests.		
Radiation Methodology		
• Development of SSME Plume Radiation Methodology used for Cycle 1.5 and approved for Cycle 2.	RTN 250-1-01	10/91
• Development and verification of plume property prediction and radiation modeling techniques for Cycle 1.5 ASRB radiation.	RTN 250-1-02	10/91
• Thermal Panel presentation of Cycle 1.5 plume radiation models.		11/91
• Continued development of the Reverse Monte Carlo Code for prediction of scattering radiation in SRB plumes.	RTN 250-1-04	3/92
• Analysis of DFI results and preparation of Cycle 1.5 ASRB sea level plume radiation models for the ET.	RTN 250-1-05	3/92
• Analysis of DFI results and preparation of Cycle 1.5 altitude adjustments for ASRB plume radiation models for the ET.	RTN 250-1-06	3/92
• Completion and verification of the ET surface description database for the Cycle 1.5 plume radiation predictions.		
• Modification of the RAVFAC viewfactor code to provide surface radiance as a function of angle at the surface in preparation for Cycle 2 radiation model improvements.		
Plume Property Prediction Methodology		
• Review of SSME plume prediction methods and comparisons of predicted radiation with DFI measurements to select the Cycle 1.5 SSME plume property models. Prepared the plume predictions for 3 altitudes.	RTN 250-1-01	10/91
• Participation in critical review of MNASA and SRB plume property predictions in the process of defining the Cycle 1.5 plume property prediction methodology.	RTN 250-1-02	10/91
• Evaluation of modifications in plume model prediction methodology in an effort to improve predictions for Cycle 2.		

OBJECTIVE	PUBLICATION	DATE
Environment Prediction		
• Cycle 1.5 plume radiation gimbal sensitivity factor definition and plume radiation environment prediction for the ET.	RTN 250-1-07 RTN 250-2-01	3/91 2/92
• Participation in Thermal Panel Critical Review of the Cycle 1.5 plume ascent environments.		
• Presentation of the Cycle 1.5 plume ascent environment models to the AFSIG at JSC in April 1992.		

WBS 1000 SECOND YEAR ACTIVITIES (10/1/92-9/30/93)

OBJECTIVE	PUBLICATION	DATE
Experimental Programs		
• MNASA-11 through 13 radiometer arrangements, theoretical comparisons and radiometer calibration.		
• Plume radiation analysis, procurement of radiometers and radiometer calibrations for TEM-11 tests.		
Radiation Methodology		
• Continued development of the Reverse Monte Carlo Code for prediction of scattering radiation in SRB plumes.	AIAA 93-0138	1/93
• Radiation predictions to evaluate plume prediction methodology improvements for the Cycle 2 environments.		
• Prepared plume radiation as a function of angle for the Cycle 2 ASRB sea-level plume.		
• Thermal Panel presentation of preliminary Cycle 2 plume radiation models.		6/93
• Investigation of the effects of scale on plume radiation.	RTN 250-1-10	8/93
• Extensive review of DFI radiometer calibration and data reduction methods to recommend correct methods for interpreting flight results in verifying plume radiation models.	RTN 250-1-11	9/93
• Proposal of method for using DFI results to derive Cycle 2 plume radiation altitude adjustment models.	RTN 250-1-12	9/93
Plume Property Prediction Methodology		
• Evaluation of modifications to plume model prediction methodology in an effort to improve predictions for Cycle 2.		
Environment Prediction		
• Investigation of application of Cycle 1.5 models to ET Generic Certification predictions.	RTN 250-1-09	8/93
• Provide additional ASRB Cycle 1 predictions.	RTN 250-2-04	9/93

WBS 1000 LIST OF PUBLICATIONS

Technical Notes (RTN)

250–01 Stuckey, C. Irvin, "Thermal Development Flight Instrumentation on Left and Right Advanced Solid Rocket Boosters," May 1992

250–1–01 Reardon, John, "SSME Plume Radiation Methodology for the Cycle 1.5 ASRB Plume Radiation Environment," October 23, 1991.

250–1–02 Reardon, J. E., Everson, J., and Smith, S. D., "Analytical Methodology for the Cycle 1.5 ASRB Plume Radiation Predictions," October 30, 1991.

250–1–03 Reardon, J. E., "Radiation Measurement Requirements for the Static Firings of the Advanced Solid Rocket Motor (ASRM)," December 31, 1991.

250–1–04 Everson, John, "A Reverse Monte Carlo Radiative Transfer Code," March 16, 1992.

250–1–05 Reardon, J. E., Everson, J., and Fulton, M. S., "Cycle 1.5 ASRB Sea Level Plume Radiation Model Description," March 16, 1992.

250–1–06 Reardon, J. E. and Fulton, M. S., "Development of Cycle 1.5 ASRB Plume Radiation Altitude and Shutdown-Spike Adjustments," March 16, 1992.

250–1–07 Reardon, J. E. and Fulton, M. S., "Cycle 1.5 ASRB Plume Radiation Reference Environments," March 16, 1992.

250–1–08 Reardon, J. E., "Revised Radiometer Locations for the ASRM Static Tests," March 5, 1992.

250–1–09 Reardon, J. E., "Evaluation of Cycle 1.5 ASRB Plume Radiation Methodology to Generic Certification Predictions for the External Tank," Aug. 31, 1993.

250–1–10 Everson, John, "Scaling of ASRM/RSRM Radiation Ratio with Motor Size," August 31, 1993

250–1–11 Reardon, John E., Shultz, Kevin P., and Everson, John, "Application of Space Shuttle Flight Data to Plume Radiation Modeling," Sep. 15, 1993.

250–1–12 Reardon, John E., Shultz, Kevin P., and Everson, John, "Adjustment Procedures for Space Shuttle DFI Radiometer Results," Sep. 30, 1993.

250–2–01 Bender, Robert L., Brown, John R., Fulton, Michael S., and Reardon, John E., "Cycle 1.5 ASRB Ascent Base Heating Environments for the External Tank," Feb. 14, 1992.

250–2–01 Bender, R. L., et al., Cycle 1.5 ASRB Ascent Base Heating Rev. A Environments for the External Tank," February 14, 1992.

250–2–04 Bender, Robert L. and Reardon, J. E., "Additional Cycle 1 Plume Induced Environments for the ASRM," September 20, 1993.

Appendix B
WBS 2000 — Ascent Plume Convection

There were two major efforts undertaken in the ascent plume convection task: definition of plume induced convective base heating and definitions of the booster separation motor plume impingement environments.

Plume induced convective base heating occurs during ascent when the booster and main engine plumes expand and interact at higher altitudes, creating a reverse flow of hot gases which flow into the base region and over base surfaces. This two-year study continued development of the convective methodology previously developed for Cycle 1 and generated nominal preflight predictions for an expanded number of body points on each of the Shuttle elements. Predictions included a convective heat transfer coefficient and gas recovery temperature specified for surface zones of nearly constant convective heating in the base of each element.

Definition of the **booster separation motor (BSM) flowfields** at ASRM separation altitudes for both the forward and aft motors is the first step in the impingement study. When the separation trajectory is defined, the plume impingement environment is defined for all affected elements (the nose of the Orbiter, the LO_2 tank and intertank of the ET, and the nose and aft skirt of the ASRB) based upon their relative positions to the ASRB during BSM firing.

WBS 2000 FIRST YEAR ACTIVITIES (10/1/91-9/30/92)

OBJECTIVE	PUBLICATION	DATE
Convective Base Heating		
• Cycle 1.5 methodology presented to ASRM Thermal Panel (11/12-14).		11/91
• Time mismatch between radiation and convection environment discussed. Progress review meeting held at REMTECH.		12/91
• Cycle 1.5 methodology approved with understanding that additional smoothing required due to 14.4 sec time shift. Plume heating environment delivery date slid two weeks until 2/14/92.		1/92
• Cycle 1.5 environment package delivered to MSFC.	RTN 250-2-01	2/92
• Reviewed Cycle 1.5 convective environments and compared with Cycle 1 and Generic Certification. Developed improved recovery temperature history to enhance convective environment trends at elevated wall temperatures.		
• Released Rev A to Cycle 1.5 environment. Presented Cycle 1.5 methodology to AFSIG panel at JSC.		4/92
• Trajectory sensitivity study for ET convective heating was drafted to help in selection of future trajectory inputs. Assessed impact of increasing ASRM nozzle exit diameter by 4 inches to convective base heating. Determined why SSME convective heating for Cycle 1 was less severe than IVBC-3 at elevated wall temperatures.		5/92
• Cycle 1.5 methodology documented. Presented salient features of trajectory sensitivity study for ET convection to Thermal Panel.	RTN 250-2-01 RTN 250-2-03	6/92
• Initiated work to define Cycle 2 methodology for Orbiter and SSMEs. Received preliminary set of ASRB body points.		7/92
BSM Plume Impingement		
• Generated Cycle 1.5 BSM plume induced environments		
- Generated 196K BSM plume		12/91
- Separation trajectory maximized impingement to Orbiter nose		1/92
- Developed pressure and heating environments to Orbiter and ET		2/92
- Orbiter: nose, forward fuselage, body flap, engine bell		

OBJECTIVE	PUBLICATION	DATE
BSM Plume Impingement (continued)		
- ET: nose, ogive, cylindrical section		
- Documentation	SECA-TR-92-05	3/92

WBS 2000 SECOND YEAR ACTIVITIES (10/1/92-9/30/93)

OBJECTIVE	PUBLICATION	DATE
Convective Base Heating		
• Updated Cycle 1.5 version of SPICE code to predict ASRB environments.		10/92
• Generated 'Cycle 2' ASRM plume induced convective environments for ASRB Body Points 2116 and 2136		10/92
• Performed analysis and conferred with Rockwell/Downey and MSFC/ED33 personnel to select conditions (trajectories) for Cycle 2 environments.		10/92
• Participated in ASRB Cycle 2 body point definition meetings. Notified by RI to use ASRM Cycle 1.5 nominal (no-fail) and RTLS (with SSME #1 engine out @ liftoff) for the Cycle 2 environment analysis; remaining abort trajectories originally due in early November were delayed. Provided quick-look ASRM 'Cycle 2' convective environments (without convective shutdown spike) for 11 ASRB body points as requested by Mr. Glen Brown.		11/92
• Coordinated Cycle 2 convective methodology environment output, Thermal Panel review and approval schedule with the Thermal Panel. Received seven suplemental Cycle 2 abort trajectories. Provided updated, consistent set of quick-look ASRM 'Cycle 2' convective environments (without the shutdown spike) for 14 ASRB body points.		12/92
• Adjusted IVBC-3 SRB zones (10 axial, with 5 circumferential cuts) to Cycle 2 characteristics exhibited by the ASRM Cycle 2 trajectories. Received 2 additional supplemental Cycle 2 abort trajectories from RI.		1/93
• Reformatted and plotted comparisons of the 11 total ASRM Cycle 2 plume heating trajectories. Started review of Orbiter and SSME flight data trends to study the transition of predominantly ASRM to SSME plume induced convective heating.		2/93
• Extrapolated $Q_c/P_c^{0.8}$ IVBC-3 curves for non-Cycle 1 ASRB zones; initiated similar study for SSME and Orbiter zones.		3/93
• Initiated development of Cycle 2 methodology for SSMEs and Orbiter. Began incorporation of SSME and Orbiter methodologies into SPICE code.		4-5/93

OBJECTIVE	PUBLICATION	DATE
Convective Base Heating (continued)		
• Prepared and presented Cycle 2 methodology to ASRM Thermal Panel.		6/93
• Automated application of gimbal amplification factors and shutdown spike adjustments.		8/93
• Generated additional Cycle 1 environments for the ASRM.	RTN 250-2-04	9/93
• Supported Thermal Panel and DFI Working Group.		10/92 - 9/93
BSM Plume Impingement		
• Calculated the exhaust plume flowfields for a single BSM plume at three staging conditions corresponding to 150,000, 180,000 and 196,000 feet altitude.	SECA TR-93-1	1/93
• Cycle 1.5 Orbiter environments caused Orbiter impact - Investigated improvements to provide relief for Cycle 2.		2/93
• Prepared geometry models for ET, Orbiter, and ASRM for Cycle 2 environments - analysis delayed - waiting on latest staging trajectories.		5/93 - 7/93

WBS 2000 LIST OF PUBLICATIONS

Technical Notes (RTN)

250–2–01 Bender, Robert L., Brown, John R., Fulton, Michael S., and Reardon, John E., "Cycle 1.5 ASRB Ascent Base Heating Environments for the External Tank," Feb. 14, 1992.

250–2–02 Bender, Robert L. and Brown, John R., "Cycle 1.5 ASRB Plume Induced Convective Base Heating Methodology," June 30, 1992.

250–2–03 Bender, Robert L. and Brown, John R., "Sensitivity of ASRM Plume Induced ET Convective Base Heating to the ASRM Cycle 1.5 Radiation and Convection Trajectories," July 10, 1992.

250–2–04 Bender, Robert L. and Reardon, J. E., "Additional Cycle 1 Plume Induced Environments for the ASRM," September 20, 1993.

SECA (Huntsville, AL) Technical Reports

SECA-TR-92–05 Smith, S. D., "Space Shuttle Orbiter and External Tank Plume Induced Thermal and Pressure Environments Due to the Space Shuttle Advanced Solid Rocket Motor (ASRM) Booster Separation Rocket Motor (BSRM) Plume Impingement During Staging," March 1992.

SECA-TR-93–1 Smith, S. D., "Space Shuttle Advanced Solid Rocket Motor (ASRM) Booster Separation Rocket Motor (BSRM) Flowfield Characterization at Staging Attitudes of 150,000, 180,000, and 196,000 Feet," January 1993.

SECA-IFR-93–15 Smith, S. D., "Interim Final Report — Analysis and Effects of the Advanced Solid Rocket Motor on the Space Shuttle Elements," September 1993.

Appendix C
WBS 3000 — Ascent Aerodynamic Heating

The prime responsibility for ASRB ascent aeroheating environments belongs to Rockwell International (RI). The objective of REMTECH's efforts is to provide MSFC with an independent check and verification of the methodology and environmental design values provided to the Shuttle project by RI.

The work performed by REMTECH was divided into the following subtasks:

Methodology Development — This subtask included reviewing trajectory constraints, trajectory heating sensitivity analyses and developing high Mach number scaling.

Coordinating Thermal Panel Activities — This subtask included schedule coordination, body point selection and methodology review.

Assessing and Verifying Design Predictions

Flight Evaluation — This subtask included coordinating DFI selection.

WBS 3000 FIRST YEAR ACTIVITIES (10/1/91-9/30/92)

OBJECTIVE	PUBLICATION	DATE
• Built standard BP file for an ET containing BPs most likely to be impacted by delaying staging.		
• Modified ETCHECK code to do log-log extrapolation of h_i/h_u data base to Mach 5.3, or use three column h_i/h_u interpolation format to include h_i/h_u's at Mach 5.3 from wind tunnel data base. Modified code checked out OK.		
• Generated preliminary environments using Cycle 1.5 hot wall trajectory compared to IVBC-3. One BP out-of-bed; all others showed mixed, but reasonable values.		
• Reviewed RI Cycle 1.5 environments and determined they are referenced to Generic Certification — not IVBC-3 — thus precluding immediate comparisons.		6/92
• Initiated action to port in Generic Certification trajectories and environment.		
• Conducted analysis of ASRB BP 187657 at S. Holmes' request and documented results.	RTN 250-3-01	8/92
• Identified modeling differences which require additional analysis.		
• Modified MINSRB, INTERP and RESADEM codes to interpolate h_i/h_u data base to Mach 5.3. Modified code checked out OK.		
• Supported DFI Working Group meetings.		

WBS 3000 SECOND YEAR ACTIVITIES (10/1/92-9/30/93)

OBJECTIVE	PUBLICATION	DATE
• Install Generic Certification environments to replace IVBC-3 as standard for comparison.		
• Compare REMTECH and RI Cycle 1.5 environments for BPs in ET standard BP file. — 50% complete.		
• Examine suspected modeling differences between REMTECH and RI. — 50% complete.		
• Continue trajectory heating sensitivity analysis. — Trajectories not available.		
• Review and identify additional BPs affected by delayed staging. — 90% complete.		
• Develop high Mach number scaling. — 50% complete.		
• Assess and verify design predictions as available. — Reviewed Cycle 1 environments.		
• Coordinate/support Thermal Panel meetings as needed — Supported June Thermal Panel Meeting.		
• Generated ASRM Field Joint Bolt Cavity aeroheating environments.		
• Generated ASRM Stiffener Rings aeroheating environments.		
• Generated heat transfer distributions upstream of ASRM Stiffener and Attach Rings during ascent.	RTN 250-3-02	9/93
• Performed analysis activities sufficient to close Thermal Panel Action Items 3 and 7.		
• Supported DFI Working Group meetings.		
• Assembled and documented DFI guidelines.	RTR 250-3-01	10/93

WBS 3000 LIST OF PUBLICATIONS

Technical Reports (RTR)

250–3–01 Engel, Carl D., Reardon, John R., Bender, Robert L., and Stuckey, C. Irvin, "Recommended Guidelines for ASRB Aerothermal DFI Development," Oct. 1993.

Technical Notes (RTN)

250–3–01 Knox, E. C., "Review and Analysis of Cycle 1 Ascent Aeroheating Environment for ASRB Body Point 187657," Aug. 1992.

250–3–02 Kirchner, Robert D., "Heat Transfer Distributions Upstream of ASRB Stiffener and Attach Rings During Ascent," Sep. 1993.

WBS 3000 LIST OF PRESENTATIONS

Progress Review Presentation - Ascent Aeroheating Status	- 12/12/91	ED33 - REMTECH
ASRM Preliminary Design Review (PDR)	- 1/30-31/92	MSFC
ASRM PDR Data Review	- 2/3-13/92	luka
Progress Review Presentation - Ascent Aeroheating Status	9/2/92	ED33 - REMTECH
ASRB Cycle 2 Body Point Definition	- 11/2-4/93	Thermal Panel - USBI
Progress Review Presentation - Ascent Aeroheating Status	- 3/18/93	ED33 - REMTECH
ASRM Field Joint Bolt Cavity Aeroheating Environment	- 6/28/93	Thermal Panel - MSFC
ASRM Stiffener Rings Aeroheating Environment	- 6/28/93	Thermal Panel - MSFC
ASRB Thermal Panel Action Item #3 Closure	- 10/27/93	Thermal Panel Telecon
ASRB Thermal Panel Action Item #7 Closure	- 10/27/93	Thermal Panel Telecon

Appendix D
WBS 4000 — Launch Stand Environments

WBS 4000 tasks involved sea level plume and plume impingement modeling to support the specification of the Shuttle/ASRM plume impingement pressure and heating loads to the Kennedy Space Center Launch Complex 39. Additional effort performed under this task was support of the NASA/MSFC PESST series of solid rocket motor diagnostic tests. These efforts were contracted to SECA, Inc., of Huntsville, AL, under the technical direction of Mr. Sheldon D. Smith. The project summary has been extracted from the SECA Interim Final Report, SECA-IFR-93–15, published in September 1993.

WBS 4000 TASK SUMMARY

Kennedy Space Center LC-39 Plume Induced Environments

The propellant change and higher chamber pressures of the ASRM compared with the RSRM have the potential for increased impingement pressures and heat loads to ground support equipment (GSE) at Launch Complex 39. Additionally, the SSV using ASRBs will fly a different liftoff trajectory than the existing SSV using RSRBs. The existing design environments are published in GP1059. The purpose of WBS 4000 is to provide updated launch induced environments to LC-39 reflecting the use of ASRBs and different trajectories.

The launch-induced environment created by the three Space Shuttle vehicle main engine (SSME) and two Solid Rocket Booster (SRB) exhaust plumes imposes high heating rates as well as high pressures on Ground Support Equipment (GSE) elements at Launch Complex 39 (LC-39). It is possible for the heating rates to be high enough to burn any given component or to weaken the component in question so that the accompanying high pressures and vibration can cause failure. The heating rate and pressure load predictive values generated under WBS 4000 are intended to assist designers in evaluating adequacy of existing specifications and to indicate areas where redesign of GSE may be considered desirable. The heating rate and pressure load values should also provide a basis for future selection of hardware, support equipment, and structures located in critical areas of the launch complex.

SECA report SECA-TR-92–04 presents the results of this study to predict the thermal and pressure environments imposed by launch-induced plume impingement on selected parts of LC-39 GSE during the ascent of the SSV. Also included is a description of the SSME and Advanced Solid Rocket Motor (ASRM) flowfields and a discussion of theoretical models used to predict the heating rate and pressure loads experienced at LC-39 during an SSV launch. Definition of the ASRM exhaust plume and of the SSME sea level exhaust plume is provided in Sections 4.1 and 4.2, respectively, of SECA-TR-92–04. Appendix A from that report also presents a simplified technique for calculating LC-39 thermal and pressure environments for points of interest and for other ascent trajectories not considered in this report. Appendix B from SECA-TR-92–04 contains a description of a computer program that provides local plume properties in the ASRM and SSME sea level flowfields.

PESST Test Impingement Measurement and Analysis Support

As part of the MSFC PESST series of solid rocket motor tests, plume impingement heating and pressure measurements are being taken to support ASRM Cycle 2 and Cycle 3 environment development. Under this task, SECA aided in the selection of the impingement measurements that are to be taken. The models that will be used to take the impingement pressure and heat rate measurements are 6, 12 and 24–inch diameter cylinders located 12.5, 15 and 25 feet from the nozzle exit plane. The measurements will be taken at the centerline of the cylinder and 30, 60 and 90 deg off the centerline at radial locations in the plumes of 0, 0.5, 1.0 and 1.5 feet. Pretest predictions of pressure and heat loads were made to determine the instrumentation range as well as to support the design of the models.

Through September 1993, one test had been performed with the 1 foot diameter cylinder located 15 feet from the nozzle exit plane. These test data are currently being analyzed using the methodology that was developed for the LC-39 environment predictions. While the analysis is in the initial stages, the preliminary evaluation of the Cycle 2 launch stand design model as applied to the PESST cylinder data is encouraging. Impingement pressure calculations along the centerline of the cylinder are within 10 percent of the measurements. The trends and levels of the predicted heating rates to calorimeter locations being analyzed compare very well with the data. A report will be produced when the analysis of all the test measurements has been completed. The results of these tests will assist in providing the Cycle 3 launch stand environments.

WBS 4000 LIST OF PUBLICATIONS

SECA-TR-92–04 Myruski, B. L., Smith, S. D., and Smith, K. C. , "Environment and Test Specification Level Ground Support Equipment for Space Shuttle System Launch Complex 39, Vol. II of II: Thermal and Pressure, Part 1 of 2: Heating Rates, Pressure Loads and Plume Flowfields, GP-1059," March 1992.

Appendix E
WBS 5000 — Reentry Heating

The primary objective of WBS 5000 is to provide reentry heating environments for use in design of the ASRB thermal protection system (TPS). The reentry environment includes aerodynamic heating, aerodynamic cooling, SSME plume impingement, and radiative and convective heating from burning gas discharged from the solid rocket motor. This task has been separated into five subtasks which include:

SSME Plume Impingement —This subtask is treated as a separate topic and is discussed under WBS 5100.

Reentry Aeroheating — This subtask covers all the activities which are required to define reentry aeroheating environments for the external surfaces of the ASRB. Activities include reviewing Shuttle flight test data, developing Mach number scaling correlations, modifying data and codes for Mach number scaling, modifying data and codes for ASRB geometry changes, methodology verification and update, final methodology documentation, generation of environment predictions including performing parametric studies and generation of final environments, and flight evaluation including DFI selection and coordination.

Reentry Venting — This subtask covers all the activities which are required to define reentry venting heating environments for the ASRB. Activities include methodology development, performing venting verification model test, documenting the venting test data, generating venting models, calculating venting environments, and flight evaluation including DFI selection and coordination.

Aft Skirt Internal Heating — This subtask covers all the activities which are required to define reentry heating environments to the ASRB internal aft skirt. Activities include methodology development modifying SRB thermal curtain opening methodology, modifying SRB heating data base for ASRB Mach numbers, examining static firing data for nozzle flame potential, modifying SRM nozzle flame heating methodology, generation of environment predictions, and flight evaluation including DFI selection and coordination.

Reentry Environment Integration — This subtask covers all the activities which are required to define an integrated reentry heating environment. Activities include integrating the plume impingement, reentry aeroheating, nozzle flame heating, and venting environments into a combined reentry environment. Other activities performed under this subtask include documenting the overall data base and generation of the reentry environments data book as well as generating an environments data tape.

WBS 5000 FIRST YEAR ACTIVITIES (10/1/91-9/30/92)

OBJECTIVE		PUBLICATION	DATE
• Document Cycle 1 Reentry Environment Methodology		RTN 250-5-03	10/91
• Document Cycle 1 Reentry Environments		RTR 250-5-01	5/92
- Nose Cap	(Zone 1)	RTN 250-5-02	10/91
- Nose Cone/Frustum	(Zone 2)	RTN 250-5-02	10/91
- Motor Case	(Zone 3)	RTN 250-5-08	12/91
	(Zone 4)	RTN 250-5-09	12/91
	(Zone 5)	RTN 250-5-11	12/91
	(Zone 6)	RTN 250-5-12	1/92
- External Aft Skirt	(Zone 7)	RTN 250-5-04	11/91
- External Base Region	(Zone 8)	RTN 250-5-05	11/91
- Internal Aft Skirt	(Zone 9)	RTN 250-5-06	11/91
- Internal Nozzle	(Zone 10)	RTN 250-5-10	12/91
- Field Joints (w/o JEPS)	(Zones 4 & 5)	RTN 250-5-16	2/91
• Document Cycle 1 Reentry Venting Environments		RTR 250-5-01 Rev A	8/92
- Baroswitch and Plenum		RTN 250-5-17	5/92
- Nose Cap/Frustum		RTN 250-5-24	9/92
- Systems Tunnel		RTN 250-5-23	9/92
• Document Reentry Trajectories			
- ASRB Cycle 2 Reentry Trajectories		RTN 250-5-03	10/91
- ASRB Cycle 3 Reentry Trajectories		RTN 250-5-07	11/91
- NLS ASRB Cycle 3 Reentry Trajectories		RTN 250-5-20	5/92
- Comparison of the Shuttle RSRB, ASRB, Cycle 2, and the NLS HLLV ASRB Cycle 3 Reentry Trajectories		RTN 250-5-22	6/92
• Perform Reentry Aeroheating Parametric Studies			
- Use of ASRB Cycle 3 Reentry Trajectories for Defining Reentry Environments		RTN 250-5-14	1/92
- Sensitivity of ASRB Reentry Aeroheating Environments to Number of Monte Carlo Reentry Trajectories		RTN 250-5-15 Rev A	6/92
- BENTRY-STATE Comparison for ASRB		RTN 250-5-18	3/92
- Parametric Analysis of ASRB Reinforcement "Stiffener" Ring Reentry Aeroheating Environments Assuming Open Cavity Flow		RTN 250-5-19	4/92

OBJECTIVE	PUBLICATION	DATE
• Environment Comparison Software (ALCC)	RTN 250-5-25	10/92
• Data Base Analysis Software (DATAMOD)	RM 250-5-01	10/92
• Update STATE Temperature Reduction Methodology — Complete		9/92
• Update STATE h_i/h_u Matrices (X_B, θ_B and eliminate usage of equivalence points) — Complete		9/92
• Develop DFI h_i/h_u Matrix File (Primary RSRB Data Base) — Complete		8/92
• Organize Reentry Aeroheating Library — 50% Complete		
• Venting		
- Venting Verification Model Test, Test Plan	RTR 250-5-02, Rev A	9/92

WBS 5000 SECOND YEAR ACTIVITIES (10/1/92-9/30/93)

OBJECTIVE	PUBLICATION	DATE
• Perform Reentry Aeroheating Parametric Studies		
- Reentry Heat Load Comparison "Cycle 1" ASRB vs. RSRB	RTN 250-5-25	10/92
- Parametric Analysis of ASRB Systems Tunnel Height - 50 % Complete		
• Organize Reentry Aeroheating Library — Complete		
• Venting		
- Venting Verification Model Test, Test Plan	RTR 250-5-02, Rev A	9/92
- Run HGF Venting Test — Complete		5/93
- Reduce Venting Test Data	RTR 250-5-03 RM 250-5-02	7/93 8/93
- Update Venting Models for Cycle 2 — 50% Complete		
- Generate Venting Models for Subsystems not Modeled in Cycle 1		TBD
• Update STATE Models for PDR Geometry and Cycle 2 Body Points — 90% Complete		
• Update Flame Heating Model to Incorporate STS-26R, -27R and -29R Data — 50% Complete		
• Update STATE h_i/h_u Data Base to Incorporate STS-26R, -27R and -29R Data — Complete		7/93
• Develop Mach Scaling Methodology		
- Correlate Flight Data (STS-26R, -27R, and -29R)	RTN 250-5-27	5/93
- Correlate Flight Data (STS-5 and -6)	RTN 250-5-30	9/93
- Correlate High Reynolds Number Wind Tunnel Data — Complete		6/93
- Update STATE Code Methodology	RTN 250-5-26 RTN 250-5-28 RTN 250-5-29	3/93 5/93 8/93
• Reentry Methodology Sources of Error — Complete		5/93
• Update Thermal Curtain Model in STATE		TBD
• Update Parachute Trajectory Heating Environments		TBD
• Generate Cycle 2 Reentry Environments and Document — 20% Complete		

WBS 5000 LIST OF PUBLICATIONS

Technical Reports (RTR)

250–5–01 Schmitz, Craig P., "The ASRB Reentry Thermal Environment Data Book — Cycle 1," May 1992

250–5–01 Schmitz, Craig P., "The ASRB Reentry Thermal Environment Data Book — Cycle 1, Rev. A," Oct. 1992

250–5–02 Palko, Richard L., "Venting Verification Model Test," June 1992.

250–5–02A Palko, Richard L., "Venting Verification Model Test — Test Plan," September 1992.

250–5–03 Palko, R. L., and Porter, J. H., "Venting Verification Model Test — Test and Data Report," July 1993.

Technical Notes (RTN)

250–5–01 Schmitz, Craig P., "ASRB Reentry Trajectory Characteristics," October 1991.

250–5–02 Schmitz, Craig P. and Stuckey, C. Irvin, "ASRB 'Cycle 1' Reentry Environments for Zones 1 and 2," October 1991.

250–5–03 Schmitz, Craig P., "ASRB 'Cycle 1' Reentry Heating Environment Statistical Methodology," October 1991.

250–5–04 Schmitz, Craig P. and Stuckey, C. Irvin, "ASRB 'Cycle 1' Reentry Environments for Zone 7," October 1991.

250–5–05 Schmitz, Craig P. and Stuckey, C. Irvin, "ASRB 'Cycle 1' Reentry Thermal Environments for Zone 8," November 1991.

250–5–06 Schmitz, Craig P. and Stuckey, C. Irvin, "ASRB 'Cycle 1' Reentry Heating Environments for Zone 9," November 1991.

250–5–07 Schmitz, Craig P., "ASRB 'Cycle 3' Reentry Trajectory Characteristics," November 1991.

250–5–08 Schmitz, Craig P. and Stuckey, C. Irvin, "ASRB 'Cycle 1' Reentry Heating Environments for Zone 3," December 1991.

250–5–09 Schmitz, Craig P. and Stuckey, C. Irvin, "ASRB 'Cycle 1' Reentry Heating Environments for Zone 4," December 1991.

250–5–10 Schmitz, Craig P. and Stuckey, C. Irvin, "ASRB 'Cycle 1' Reentry Heating Environments for Zone 10," December 1991

250–5–11 Schmitz, Craig P. and Stuckey, C. Irvin, "ASRB 'Cycle 1' Reentry Heating Environments for Zone 5," December 1991.

250–5–12 Schmitz, Craig P. and Stuckey, C. Irvin, "ASRB Cycle 1 Reentry Environments for Zone 6," January 1992.

250–5–13 Kirchner, Robert D., "SRB Reentry Hi/Hu Data Base Revision with STS-27R and 29R," January 1992.

WBS 5000 LIST OF PUBLICATIONS (continued)

250–5–14 Schmitz, Craig P. and Shultz, Kevin M., "Usage of ASRB 'Cycle 3' Reentry Trajectories for Defining Reentry Environments," January 1992.

250–5–15 Schmitz, Craig P., "Sensitivity of ASRB Reentry Aeroheating Environments to Number of Monte Carlo Reentry Trajectories," January 1992.

250–5–16 Schmitz, Craig P., "ASRB 'Cycle 1' Reentry Heating Environments for Field Joints without JEPS," February 1992.

250–5–17 Walker, David L. and Schmitz, Craig P., "ASRB Baroswitch Tube and Plenum Heating," February 1992.

250–5–18 Shultz, Kevin M. and Schmitz, Craig P., "BENTRY-STATE Comparison for ASRB," March 1992.

250–5–19 Schmitz, Craig P., "Parametric Analysis of ASRB Reinforcement 'Stiffener' Ring Reentry Aeroheating Environments Assuming Open Cavity Flow," April 1992.

250–5–20 Schmitz, Craig P. and Evers, Annette G., "National Launch System (NLS) Heavy Lift Launch Vehicle (HLLV) ASRB "Cycle 3" Reentry Trajectory Characteristics," May 1992.

250–5–21 Evers, Annette G. and Schmitz, Craig P., "ASRB 'Cycle 1' Reentry Heating Data Base," May 1992.

250–5–22 Evers, Annette G. and Schmitz, Craig P., "Comparison of the Shuttle RSRB, ASRB 'Cycle 2,' and the NLS HLLV ASRB 'Cycle 3' Reentry Trajectory Envelopes," June 1992.

250–5–23 Evers, Annette G. and Schmitz, Craig P., "ASRB 'Cycle 1' Systems Tunnel Venting Design Environment," Sep. 1992.

250–5–24 Schmitz, Craig P. and Walker, David L., "ASRB Cycle 1 Nose Cone Internal Design Venting Environment," September 1992.

250–5–25 Reed, Christopher M. and Stuckey, C. Irvin, "Reentry Heat Load Comparison 'Cycle 1' ASRB vs. ASRB," Oct. 1992.

250–5–26 Schmitz, Craig P. and Reed, Christopher M., "Mach Effects on SRB Reentry External Interference Factors Using STS-27R and —29R Flight Data," March 1993.

250–5–27 Kirchner, Robert D., "SRB Reentry Interference Factor Data Base Revision for Internal Aft Skirt Locations with Nozzle On," May 1993.

250–5–28 Schmitz, Craig P. and Reed, Christopher M., "Mach Effects on SRB Reentry Internal Aft Skirt Aeroheating Interference Factors," May 1993.

250–5–29 Schmitz, Craig P. and Reed, Christopher M., "Mach Effects on SRB Reentry Aeroheating Protuberance Interference Factors," August 1993.

WBS 5000 LIST OF PUBLICATIONS (continued)

250–5–30 Kirchner, Robert D., SRB Reentry h_i/h_u Data Base Revision for Flights STS-5 and STS-6, September 1993.

Technical Memoranda (RM)

250–5–01 Fulton, Michael S., "SRB Reentry Data Base Analysis Software — DATAMOD User's Guide," Oct. 1992.

250–5–02 Palko, Richard L., "Analysis of Vent Box Heat Flux," August 25, 1993.

WBS 5000 LIST OF PRESENTATIONS

Progress Review Presentation - Reentry Heating Status	- 12/12/91	ED33 - REMTECH
ASRM Preliminary Design Review (PDR)	- 1/30-31/92	MSFC
ASRM PDR Data Review	- 2/3-13/92	Iuka
ASRB Altitude Sensing System Venting Environments Schedule and Analysis	- 3/12/92	ASRB IEWG - USBI
ASRB Environments and Thermal Assessment	- 4/9/92	MSFC - ED33
ASRB Reentry Venting Environments Schedule and Analysis	- 4/16/92	ASRB IEWG - USBI
ASRB/RSRB Reentry Environments Data Base	- 5/92	ED33 - REMTECH
Progress Review Presentation - Reentry Heating Status	- 9/2/92	ED33 - REMTECH
ASRB Cycle 2 Body Point Definition	- 11/2-4/93	Thermal Panel - USBI
Progress Review Presentation - Reentry Heating Status	- 3/18/93	ED33 - REMTECH
ASRB Induced Environments Working Group - Reentry Environments Status	- 4/28/93	ASRB IEWG - USBI
DFI Briefing - Internal Aft Skirt - DFI, Gas Temperature Probe and Pressure Probes	- 3/93	ASRM DFI Working Group

Appendix F
WBS 5100 — SSME Plume Impingement

Following separation from the continuing STS vehicle, a series of environments affect the ASRB. These environments are collectively referred to as reentry environments. The initial induced environment to the spent ASRB following separation is that resulting from the combined SSME plumes impinging on the ASRB aft surfaces. This is the environment analyzed under subtask WBS 5100. Definition of this environment requires separate and distinct methodology (when compared with reentry aerodynamic heating) and has been treated as a separate topic in our overall contract effort.

The SSME plume impingement analysis was deferred until the summer of 1993 because the analysis requires separation trajectory definitions which were not available until that time. The impingement analysis is currently under way (September 1993) by REMTECH with SSME plume inputs provided by SECA.

WBS 5100 TASK SUMMARY

This study is on-going and has not been completed or formally documented at the time of this interim final report. Several important activities have been under way for several months and are summarized in the following paragraphs.

As part of this effort, SECA, Inc., generated three SSME plumes which were transmitted to Rockwell/Downey to assist in the trajectory determination. These plumes were generated corresponding to staging conditions at 150K, 180K and 200K feet and were generated using the method of characteristics code. The input data files and binary flowfield files were transmitted on magnetic tape in a VAX-VMS format.

Work was initiated in June 1993 to define the SSME plume impingement environment to the ASRBs following separation. Previous documentation of SSME plume impingement methodology was reviewed and the PLIMP code with the NCAR graphics package was exercised. The NCAR graphics program is an integral part of the PLIMP routine in that it allows the calculation and display of the input shapes and also displays the output as color contours on the shapes. The shapes necessary to determine plume impingement were determined and checked for accuracy. The MOC input for the 150,000, 180,000 and 210,000 foot SSME plumes was provided from SECA; however, due to time constraints, only the 180,000 foot plume was used for the PLIMP runs. The single SSME plume was increased by $\sqrt{3}$ to generate an equivalent plume representing the three SSME plumes.

The trajectory for the ASRBs after separation and during plume impingement has not been defined, so a number of arbitrary trajectories were used to check the impingement heating procedure (table below).

Trial Trajectories and Resultant Max Heating Rates

X (ft)	Y (ft)	Z (ft)	ϕ	θ	ψ	$\dot{q}_{max}$ (Btu/ft^2-sec)
8.0	-20.875	-30.0	0.0	-12.0	0.0	0.0
58.0	-20.875	-42.0	0.0	-12.0	0.0	0.0
108.0	-20.875	-54.0	0.0	-12.0	0.0	0.0
8.0	-20.875	-30.0	0.0	18.0	-30.0	80.3
58.0	-20.875	-42.0	0.0	18.0	-30.0	37.0
108.0	-20.875	-54.0	0.0	18.0	-30.0	5.2

The X, Y, and Z positions shown are the Xb = 200 (nose) position relative to the plume which has its origin at the nozzle exit, X-axis 12 deg above the ASRB centerline, Y-axis pointing to the right, and Z-axis rotated 12 deg forward of vertical. The angles are the rotations defined in the PLIMP documentation. The first three positions represent a trajectory in which the ASRB simply moves straight back along its X-axis 150, 200, and 250 feet. The second three are similar except the ASRB aft end is pitched up 30 deg and yawed right (into the plume) 30 deg. Representative maximum heating rates are shown, and it is clear that high heating may occur.

WBS 5100 LIST OF PUBLICATIONS

- No formal documentation has been completed.
- Informal interim data from completed analyses are available from REMTECH upon request.

Appendix G
WBS 6000 — NLS Impact Study

The National Launch System, or NLS, was the name assigned to the Joint Defense Department/NASA program for the proposed family of new launchers which was initiated in spring 1991 and continued through fall 1992. It promised to develop efficient, new launch vehicles for military, scientific and commercial payloads. The NLS program was structured to develop two launch vehicles which had common elements in the core stage. One early concept considered utilizing two or four ASRMs to augment the core stage thrust which was to be provided by an arrangement of multiple Space Transportation System Main Engines (STMEs).

Modification 5 to Contract NAS8–39235 expanded the scope of work to include an assessment of the impact of the ASRMs on the base heating environment of the NLS vehicles. The study was conducted in spring and summer of 1992 and involved several tasks directed at methodology development plus environment predictions for the NLS base region.

Two main tasks were addressed in the area of methodology development.

- Reevaluation of appropriate historical launch vehicle flight and model data to assess plume convective heating to selected body points on the base region of the NLS.
- Development of NLS specific base heating testing requirements and test plans required to eliminate conservative assumptions inherent in the currently available base heating data base.

Environment predictions were made for typical base region locations on a variety of NLS concepts. A complete environment package was generated for the NLS 2 650K STME vehicle.

WBS 6000 TASK SUMMARY

Prior to the contract modification authorizing the NLS impact study, a preliminary Cycle 1 NLS base heating environment had been generated to initiate the design evaluation process. These Cycle 1 base heating environments for the NLS 1.5 stage vehicle were based upon "upper limit" methodology and conservative assumptions and, consequently, had significant impact on selection of the thermal protection system (TPS) for the base region. Following publication of the Cycle 1 environments, analyses continued in an attempt to improve our understanding of the low altitude convective base heating which was the largest contributor to the high heating levels specific for Cycle 1. A working group was formed at MSFC to direct this follow-on analysis and to coordinate the combined activities of the flowfield, environment, and thermal response analysts.

REMTECH participated in this working group and developed the engineering approach (updated methodology) used to generate the NLS 2 650K STME environments. The NLS 2 environments were specified for 13 body point locations in the base region of the NLS 2 vehicle, which was the latest designation for the six-engine 1.5 stage concept. The NLS 2 engineering approach utilized scaled Saturn V flight data and resulted in environments substantially lower than Cycle 1.

WBS 6000 LIST OF PUBLICATIONS

Technical Notes (RTN)

250–6–01 Bender, R. L., et al., "August 1992 NLS 2 650K STME Base Heating Environments," August 7, 1992.

Appendix H
WBS 7000 — Molten Al_2O_3 Radiation Characteristics

This study involved a series of experiments to determine the effects of atmosphere on the Index of Refraction of molten alumina (Al_2O_3). It was contracted to Physical Sciences, Inc. (PSI) of Andover, MA, in August 1992 as a one-year study under the technical direction of Dr. Terry Rawlins. The project summary from the PSI final report synopsizes the objectives, accomplishments, and conclusions from the study.

WBS 7000 TASK SUMMARY

Final Report PSI-2223/TR-1272 describes the results of experimental measurements to determine the effects of individual gas phase species, representative of the SRM plume environment, on the radiative characteristics and imaginary refractive indices of Al_2O_3 particles at high temperatures, near and above the melting point. The experiments consisted of multispectral (0.5 to 5 μm) emission and extinction measurements on dilute clouds of pure-form, submicron α–Al_2O_3 particles heated in selected gaseous environments in a shock tube. The bath gases (diluents) used include Ar, O_2, CO, and CO_2. The particles and bath gas were heated by reflected shock waves to selected temperatures of 2000 to 3000 K and pressures of 10 to 30 atm, where they remained at constant temperature and density for 1.5 to 2 ms. At the end of this steady period, the particles and gas were rapidly cooled by a rarefaction wave, giving cooling rates in excess of 10^5 deg/s, similar to conditions in the expanding rocket exhaust plume. Thus each test shock gives information on the initial particle cloud heating in the reflected shock, the particle/gas radiative signature during the steady high-temperature period, and the particle radiative phenomena associated with rapid cooling.

Observations of visible and infrared emissivities during the steady high-temperature period were normalized to laser extinction measurements of the injected particle number densities, to determine size-averaged absorption cross sections for the molten particles. These values were converted to values of the imaginary index k, using Mie theory calculations accounting for the actual measured size distribution of the particles. The value of k observed for molten Al_2O_3 particles in an argon bath were consistent with those we have determined previously at similar temperatures. However, the values of k observed in argon were significantly larger than those observed in 40 percent O_2/Ar mixtures. Values of k observed in CO/CO_2/Ar mixtures appeared to be comparable to those observed in argon at similar temperatures. These observations are consistent with our expectation that, in an oxygen-poor or reducing environment, the molten particles will develop oxygen deficiencies through evaporative losses and structural randomization, resulting in increased values of k in the visible and short-wavelength infrared.

The particle radiative properties were also observed during the rapid cooling stage of the rarefaction wave. The particle temperatures were monitored radiometrically, and were observed to decrease rapidly to temperatures well below the melting point. In Ar, the results were consistent with our earlier observations, which showed large, essentially liquid-like values of k for apparently solid, rapidly cooled particles. This behavior suggests the formation of a metastable solid phase. A similar effect was observed in CO/CO_2/Ar. However, in O_2/Ar mixtures, the apparent radiometric temperatures remained nearly constant even though the pressure measurements showed that the gas phase temperatures decreased substantially. This suggests that gas phase O_2 is reacting vigorously with exposed Al on the surfaces of the particles, resulting in substantial chemical heat release to slow down the particles' cooling rate during the expansion period.

These results have significant implications for the modeling of particulate radiative properties and heat transfer in SRM plumes. First, it is clear that the inherent optical properties of molten Al_2O_3 particles are strongly affected by the composition of the bath gas. This may be caused by chemical exchange processes between the gas and the material; however, more comprehensive investigations are required to test this hypothesis. Second, the optical properties of the solid are clearly affected by the physics of the rapid cooling process, probably through the formation of metastable phase(s) having enhanced electrical and optical properties. Third, oxidative attack on hot particles may result in significant chemical heat release which would impact the particle cooling rates and associated heat transfer phenomena.

WBS 7000 LIST OF PUBLICATIONS

PSI-2223/TR-1272 Rawlins, W. T., Du, Hong, Foutter, R. R. and Parker, T. E., "Final Report — Experiments to Determine the Effects of Atmosphere on the Index of Refraction of Molten Alumina (Al_2O_3)," Physical Sciences Inc., Andover, MA, September 1993.